

# Researchers Determine Chernobyl Liquidators' Exposure

**O**N April 26, 1986, an accident at the Chernobyl nuclear reactor in the former Soviet Union released an enormous number of fission products into the atmosphere and over a large portion of the planet. With about 100 million curies released in the 10 days following the initial explosion, the accident was the largest single nonmilitary release of radioactivity in history—and one of the largest environmental disasters ever.

During the first year after the accident, about 25,000 people, mainly Soviet Army troops, were dispatched to the site to clean up the accident. These so-called liquidators were estimated to have received doses of up to 70 centigrays (a gray is the international unit for measuring absorbed ionizing radiation and is equivalent to 100 rads, or 1 joule per kilogram). In the following three years, another half-million people assisted the effort and are estimated to have received lower doses (about 10 to 25 centigrays).

The tasks performed by liquidators included shoveling core material off the roof of the undamaged part of the building, operating heavy equipment to contain contaminated soil, and building a concrete sarcophagus around the destroyed reactor. Depending upon the intensity of radiation exposure associated with their assigned task, most liquidators received radiation exposures over a period of at least several days, and in some cases over many weeks.

Lawrence Livermore biomedical scientists began studying the Chernobyl accident almost as soon as it occurred as part of a Department of Energy effort to help assess the accident's biological effects. The Livermore assistance, which continues today, takes advantage of the Laboratory's longstanding expertise in evaluating human exposures to ionizing radiation and determining their health risks. Livermore scientists have forged numerous and often close scientific relationships with their Russian and Ukrainian counterparts that endure today in collaborations, mutual assistance, informal communications, and visits.

## Techniques to Monitor Damage

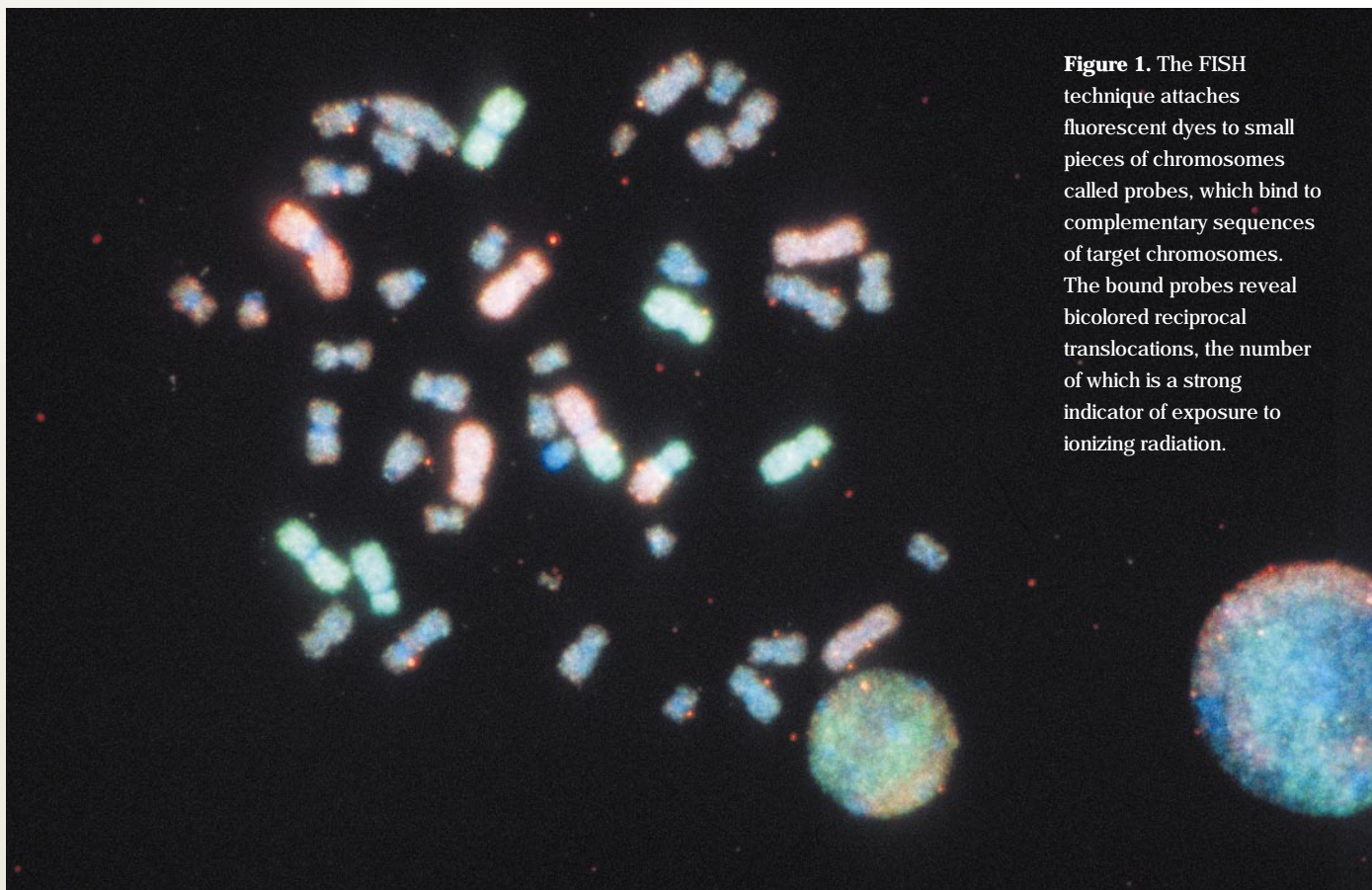
Lawrence Livermore studies on Chernobyl liquidators have focused on three techniques—two of them developed at Livermore in the 1980s—that are in wide use today to monitor

genetic damage in people. The techniques are called biodosimeters because they measure changes in cells to infer the biological consequences of the “dose,” or energy deposited in human tissue from ionizing radiation. (In contrast, a standard dosimeter uses a piece of sensitive film that responds proportionally to ionizing radiation.)

The glycophorin A (GPA) assay was first used to study Chernobyl liquidators who demonstrated immediate symptoms known as acute radiation sickness. Within days of the accident, a Livermore group (at that time led by Ron Jensen, now at the University of California at San Francisco) began receiving blood samples from people who received high exposures. The evaluation by Livermore's Richard Langlois found that the response of GPA to high doses of radiation was similar for A-bomb survivors and Chernobyl liquidators. The investigators also found that age and smoking had little effect on the frequency of the GPA null mutants.

The GPA assay measures the number of red blood cells that have a change in the M or N form of the GPA gene. For people whose cells have both forms of the gene, damage to the M form of the gene, for example, can result in a “null” mutation. In such a case, all descendants of that cell fail to make the M protein. Using flow cytometry and cells stained with color-coded antibodies specific to the M and N forms, scientists can study millions of red blood cells from a small blood sample in a few minutes without the need for cell culturing. (See [August 1987 \*Energy & Technology Review\*](#), “A New Assay for Human Somatic Mutations,” pp. 21–26, and [April/May 1992 \*Energy & Technology Review\*](#), “The Glycophorin-A Assay: A Ten-Year Retrospective,” pp. 1–18.)

The second technique measures the frequency of mutations of the hypoxanthine phosphoribosyltransferase (HPRT) gene in lymphocytes. This assay was not invented at Livermore, but Laboratory researchers have greatly expanded understanding of the assay's ability to detect DNA damage from ionizing radiation. Livermore biomedical scientist Irene Jones performed work in the 1980s using mice to test the assay. She also developed a database on healthy people to serve as a baseline for the frequency and molecular nature of HPRT mutations.



**Figure 1.** The FISH technique attaches fluorescent dyes to small pieces of chromosomes called probes, which bind to complementary sequences of target chromosomes. The bound probes reveal bicolored reciprocal translocations, the number of which is a strong indicator of exposure to ionizing radiation.

A third technique called FISH (fluorescence in situ hybridization), which was developed at Livermore and is currently used around the world, has been applied to Chernobyl liquidators as well as to others suspected of receiving ionizing radiation or of being exposed to potentially damaging chemicals. FISH measures chromosome damage by detecting the number of reciprocal translocations, or broken pieces of chromosomes, in lymphocytes that rejoin in a mismatched way. Livermore scientists have shown that the number of reciprocal translocations is proportional to exposure to ionizing radiation at low doses. What's more, unlike some biodosimeters, including other types of chromosome alterations, the frequency of reciprocal translocations is sufficiently stable with time (even over several decades) to permit retrospective dosimetry and can be measured accurately at low levels of radiation.

The FISH technique uses chromosomes from cultured lymphocytes. Fluorescent dyes are attached to small pieces of chromosome sequences called probes, which bind to complementary sequences of the target chromosomes. The

bound probes reveal the extent of reciprocal translocations because they appear bicolored under a microscope using fluorescent light (Figure 1) and can thereby be counted easily to determine a person's likely exposure to ionizing radiation. (See *October/November/December 1992 Energy & Technology Review*, "Chromosome Painting," pp. 11–26, and the *November/December 1995 S&TR*, "The Genetic Contribution of Sperm: Healthy Baby or Not," pp. 6–19.)

### **Applying Biomarkers to Russian Liquidators**

The usefulness of all three biodosimeters for measuring small or moderate amounts of ionizing radiation is being demonstrated in an eight-year study (1992 to 1999) of a large group of liquidators. The study, conducted for the National Cancer Institute and directed by Livermore scientist Irene Jones, focuses on a population of about 300 Russian liquidators who were assumed to have been exposed to doses of about 5 to 25 centigrays. The study also includes 300 matched controls from Russia of about the same age and with similar smoking histories.



**Figure 2.** Livermore biomedical scientists Jim Tucker (second row, second from left) and Richard Langlois (second row, far right) recently visited the laboratory of Dr. Irina Vorobstova (front row, left) at the Laboratory of Radiation Genetics, Central Research Institute of Roentgenology and Radiology, St. Petersburg, Russia. Visits such as these have fostered successful collaboration on the health effects of radiation dose resulting from the Chernobyl disaster.



Because physical dosimetry was difficult to perform on the half-million liquidators, the Livermore team decided to estimate the Russians' exposure through biodosimetry. They also reasoned that because people have different susceptibilities to radiation toxicity, biodosimetry is a more accurate indicator of cancer risk than accurate physical dosimetry. (Physical dosimetry measures radiation incident upon the body, but biodosimetry measures cellular injury resulting from that radiation.)

### Recognizing Statistical Power

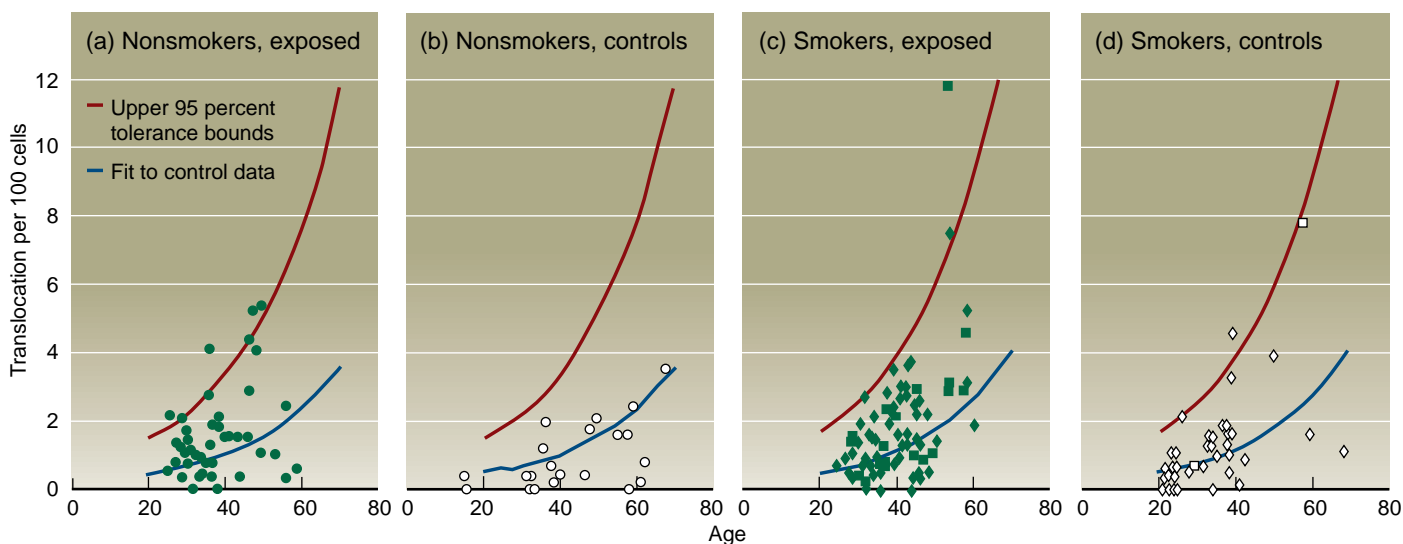
Livermore experts also recognized that the large number of liquidators would give their study the same kind of statistical power that had made previous studies on Hiroshima and Nagasaki A-bomb victims important to human radiation biology. However, it would provide information for different radiation exposure conditions. While A-bomb survivors received instantaneous external exposures, Chernobyl exposures were complex mixtures of internal and external exposures over a period of time and, in some cases, during several separate work assignments.

To increase the statistical power of dose-effects studies, the Livermore investigators are collaborating with researchers from the Applied Ecology Research Laboratory, Ministry of Health and Medical Industry of Russia in Moscow; the Laboratory of Radiation Genetics, Central Research Institute of Roentgenology and Radiology, St. Petersburg, Russia (Figure 2); and the Tula Diagnostic Clinic of the Scientific Institute of Modern Medical Technologies, Tula, Russia. Blood samples are drawn in St. Petersburg, Moscow, and Tula and shipped by air to Livermore.

The results so far show FISH to be sensitive to the exposures of Chernobyl liquidators, with the HPRT assay being less sensitive and the GPA assay, which proved highly valuable for studies of A-bomb survivors and more highly exposed Chernobyl liquidators, showing no difference between the exposed and control populations (Figure 3). The Livermore team says its population of liquidators received on average a dose of about 15 centigrays, as determined by FISH. Such a radiation dose is roughly equivalent to aging about 10 years or to smoking cigarettes regularly. The expected health consequences to the population under study from such an exposure are small.

Livermore researcher Jones notes that the sensitivity to detect the effect of radiation exposure is increased by knowing the age and the smoking habits of the individual, because both characteristics contribute to the damage in their cells. However, she says it is impossible to determine the health risk of any one individual who received a specific amount of ionizing radiation, especially at the lower doses that do not cause acute health effects. Each individual has a different complement of genes that determine how well they can repair damage from ionizing radiation and other sources. Personal habits such as smoking, drinking, and diet add to the genetic damage that accumulates in cells. "It is the sum of all damage and the body's response to that damage that determines the risk of cancer and other health effects," she says.

In a separate study led by biomedical scientist Joe Lucas, Livermore researchers applied FISH to a subset of Chernobyl liquidators suspected of receiving a large dose of ionizing radiation. They reconstructed doses for 27 Chernobyl liquidators from the frequency of translocations measured in their lymphocytes. Of the 27 individuals, 15 are



**Figure 3.** A Livermore study is using FISH to show that ionizing radiation from the Chernobyl accident has increased the number of chromosome translocations in (a) the liquidator population compared with (b) a control group. The FISH study also revealed the greater number of translocations seen in (c) liquidators who smoke cigarettes (solid diamonds) or a stronger tobacco called papirossi (solid squares) compared with (d) the control population of smokers (open diamonds and squares).

being treated for radiation sickness. The remaining 12 show no medical symptoms.

“FISH has worked extremely well on Chernobyl victims,” says Lucas, one of the original developers of FISH. He notes that the technique is useful because not every liquidator had a dosimeter, and memories of the nature and duration of work assignments for most workers are not reliable.

### Questions Still Unanswered

Current studies at Livermore and at other research centers are addressing some of the unanswered questions about the assays, such as their sensitivity to low doses, how intensity of radiation exposure affects the response, the persistence of chromosome translocations, and the degree to which factors other than radiation affect them. Jones and her colleagues, for example, are studying the extent to which the type of chromosome aberration affects its persistence in human blood cells, which could change the relationship between translocation frequency determined by FISH and radiation dose as time passes after exposure.

Another major goal of the research will be to understand why people differ in the effect that the same dose of radiation has on their cells. One part of this effort has been started—identifying the differences in the DNA repair gene sequence in people. The next big challenge will be to determine how these differences affect the capacity to repair damaged DNA and if these differences are related to long-term health.

The Lucas group is collaborating with colleagues at Columbia University on a promising method to detect cellular damage among the liquidators. The method is based on measuring the formation of micronuclei, which are secondary and much smaller cell nuclei that form in eye cataract tissue as a result of radiation. The group is also working on an enhancement to FISH that is faster, more accurate, and more sensitive by counting individual chromosomes in liquid suspension instead of on a microscope slide.

In the meantime, Livermore radiation-effects researchers are working with collaborators in Ukraine, Russia, Estonia, and Israel (where some liquidators have immigrated) to apply biodosimeters such as FISH and GPA in their own laboratories.

It seems clear that despite its disastrous environmental consequences, the Chernobyl accident has spawned deeper understanding about the health effects of ionizing radiation and, in the process, spurred stronger international cooperation.

— Arnie Heller

**Key Words:** biodosimeter, Chernobyl, FISH (fluorescence in situ hybridization), glycophorin A (GPA), hypoxanthine phosphoribosyltransferase (HPRT).

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# Target Chamber's Dedication Marks a Giant Milestone

**T**HE June unveiling of a 130-ton (118,000-kilogram) gleaming metal sphere some 10 meters in diameter marked a much-anticipated and highly celebrated milestone for the Department of Energy's National Ignition Facility, now under construction at Lawrence Livermore. A large crowd of employees and guests, including Energy Secretary Bill Richardson, was on hand for the dedication of the giant target chamber for NIF, currently the nation's largest science construction project.

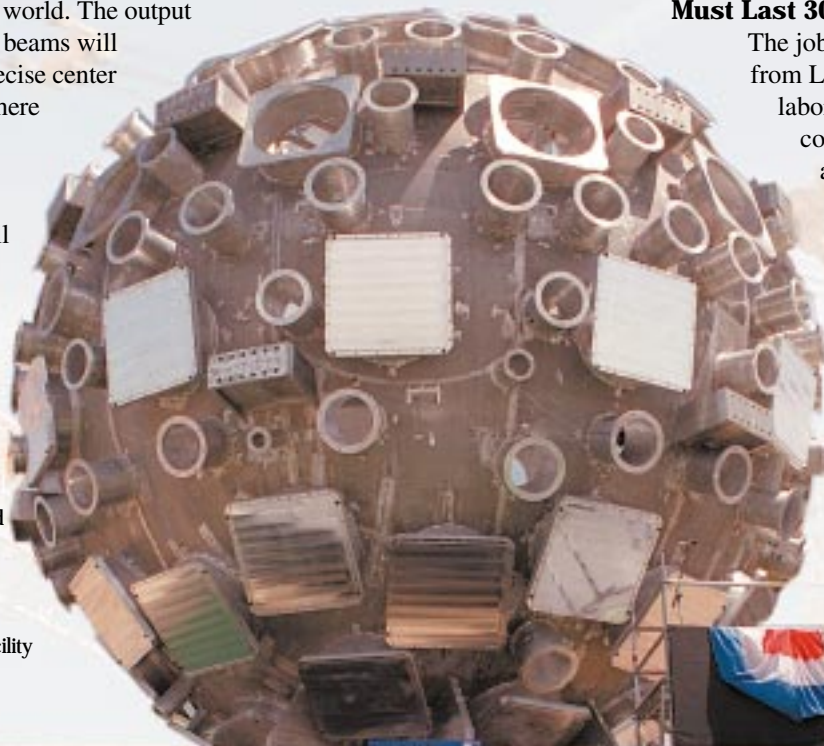
The dedication marked the on-time completion of NIF's single largest piece of equipment. The \$14.5-million vessel will serve as the working end of the largest laser in the world. The output of NIF's 192 laser beams will converge at the precise center of the chamber, where conditions of deep vacuum and temperatures far below freezing will support experiments only dreamed of for decades.

Energy Secretary Bill Richardson addresses the crowd that attended the June 11, 1999, dedication of the National Ignition Facility target chamber.

NIF's beams will enter the chamber in two-by-two arrays to illuminate 10-millimeter-long gold cylinders called hohlraums enclosing 2-millimeter capsules containing deuterium and tritium, isotopes of hydrogen. The two isotopes will fuse, thereby creating temperatures and pressures resembling those found only inside stars and in detonated nuclear weapons—but on a minute scale. By recreating these extreme conditions in a carefully instrumented laboratory setting, NIF will serve as an essential facility in DOE's Stockpile Stewardship Program to ensure the safety and reliability of the nation's nuclear arsenal.

## Must Last 30 Years

The job facing a team of engineers from Livermore and Sandia national laboratories was to design and construct a vessel that would last at least 30 years, withstand earthquakes as well as debris and gamma radiation from experiments, maintain deep vacuum and ultrafreezing environments required for experiments, and accommodate nearly a hundred diagnostic instruments, 192 beamlines, and associated optics and equipment—and do it all within budget and on schedule.



Lawrence Livermore National Laboratory



“There was never any doubt we could build it,” says Livermore mechanical engineer Dennis Atkinson. In that respect, he says, the assignment was similar to other NIF construction projects. “They are all challenging, but we know we can accomplish them.”

The engineering team, led by Livermore’s Vic Karpenko and Dick Wavrik of Sandia National Laboratories, first consulted with laser scientists, optical experts, target physicists, laser physicists, and facility designers at Lawrence Livermore and Los Alamos national laboratories, the University of Rochester, and the Defense Threat Reduction Agency about their requirements for the target chamber. These requirements included the absolute synchronization of laser beams arriving at the target simultaneously, fixed focal plane distances from the final optics to the targets, close proximity of myriad instruments, and ease of ingress and egress of systems to transport, hold, and freeze the tiny targets. The result was an 11-centimeter-thick spherical vessel measuring about 10 meters in internal diameter, with 190 holes of varying diameters located over its surface to accommodate the beamlines, diagnostic instruments, and other equipment.

With the final dimensions agreed upon, the engineering team reviewed manufacturing options. One idea was to fashion the target chamber from a mosaic of small, identical (1.8- by 1.8-meter) pieces. However, such a mosaic would require considerable on-site welding and thereby increase costs.

The team also investigated having the vessel built in a machine shop as two hemispheres and then transported to Livermore for assembly. That notion was dropped because it posed transportation problems, and the vessel, with its complicated distribution of portholes, did not lend itself to being fabricated as two equal hemispheres.

### Giant Volleyball

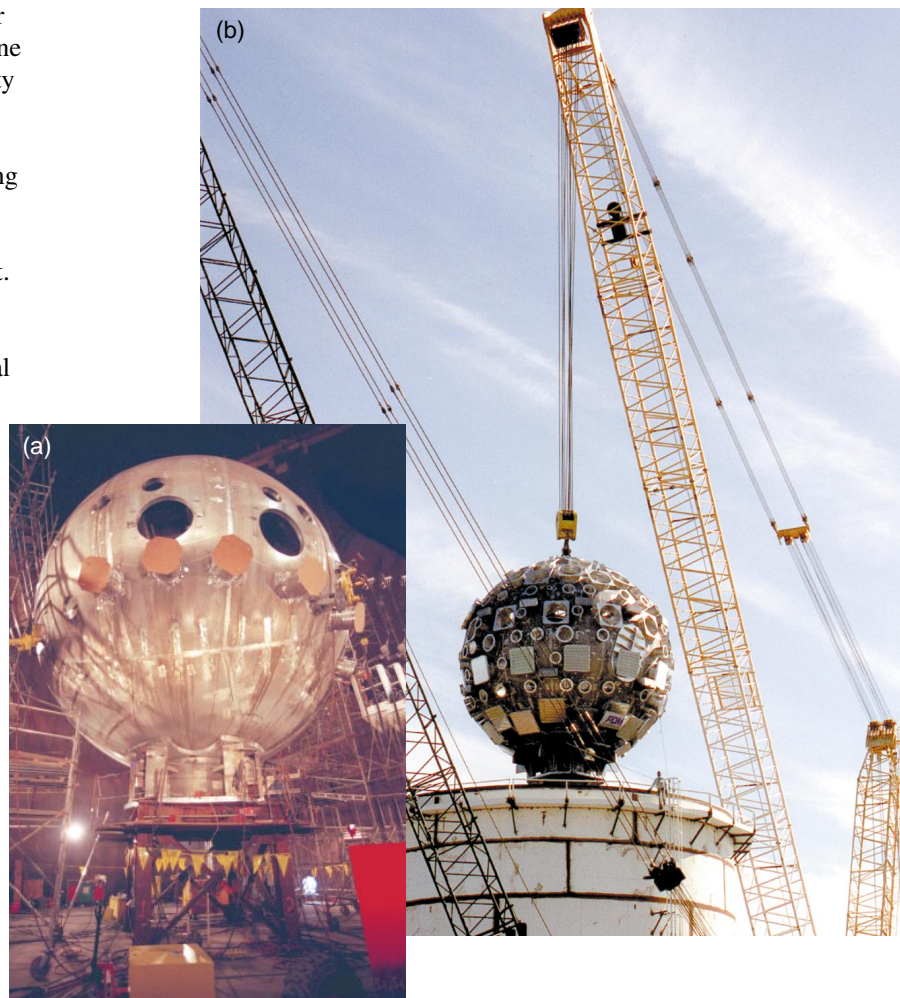
The team finally agreed upon an expanded cube (6 sides) with 3 plates per side (18 plates total) to minimize welding length and overall cost. The design, looking like a giant volleyball, features 6 symmetric middle plates and 12 asymmetric outer plates. As manufactured, the 18 aluminum plates measure 2.4 by 6.9 meters and weigh about 7.5 tons each.

There was uniform agreement that the vessel should be manufactured from aluminum, specifically the aluminum alloy 5083-0. The same alloy, notes mechanical engineer Wavrik, is used in harsh marine environments such as ship superstructures.

The completed vessel was estimated to weigh some 130 tons. An outer concrete skin and final optics would add 200 tons each, for a total of nearly 530 tons. Given that estimate of final weight and the number of holes that needed to be drilled, the designers decided on a plate thickness of

11 centimeters. Although this was more than was needed theoretically, it gave the chamber the strength of a substantial structure in its own right rather than a simple vessel to contain experiments.

A prime consideration was ease of fabricating the 18 plates. “We wanted to make sure we didn’t design something that would be difficult to manufacture,” says Atkinson. The team chose as manufacturing contractor Pitt–Des Moines Inc., which has extensive experience fabricating vessels, from nuclear power plants to water storage tanks.



(a) The target chamber being assembled within a temporary cylindrical steel structure with a removable roof. This progress photograph was taken in March 1999 when all of the plates making up the chamber were in place and some of the 190 portholes to accommodate beamlines and diagnostic instruments had been cut in it. (b) The completed target chamber being removed from the temporary assembly structure.

Pitt-Des Moines assembled an international team of subcontractors. Manufacturing began in the fall of 1997, when the plates were poured at the Ravenswood Aluminum Mill in Ravenswood, West Virginia. The plates were shipped to forming subcontractor Creusot-Loire Industries in France, where the plates were heated to 315°C and then shaped in a giant press to the proper spherical geometry.

### From France to Pennsylvania

The formed plates were shipped weekly in pairs from France to Precision Components Corp. in York, Pennsylvania, where they were trimmed and weld joints were prepared. Three plates at a time were trucked to Livermore. The first plates to arrive were those with the highest tensile strength to provide a strong base for the entire vessel.

Assembly and welding activities at Livermore were performed in a temporary cylindrical steel enclosure looking much like an oil or water tank. Constructed in June 1998, the temporary structure measured 18.3 meters in diameter and 18.9 meters high and rested on a 61-centimeter-thick concrete slab. The enclosure featured a roof to ensure temperature control and keep out rain. The roof was removed only to permit cranes to lift the plates into place as soon as they arrived and for lifting out the assembled vessel for its dedication and transport to its final home in the target building.

After the bottom three plates were welded together to form a supporting base, the other plates were lowered into place and held together with guy wires until welded. Each welded seam required 150 passes over a like number of layers of thin aluminum wire for a smooth, nonporous finish. Although time-intensive, this approach minimized thermal stress to the aluminum plates.

The porthole drilling process required laser instrumentation both to mark the port location and to drill the pilot holes. Most of the ports are arranged in pairs, one directly on the opposite side of the chamber from the other. In this way, the two opposing ports may be used for alignment purposes.

Seventy-one larger holes 1.16 meters in diameter will accommodate the final optics assemblies (FOAs), the last element of the main laser system. An additional port, which includes an FOA port, measures 1.67 by 1.16 meters and provides access for testing nuclear-weapons effects. (Designers have provided the capability to receive and transport a large diagnostic package to this port.) Weldnecks with thick flanges were secured to the ports to accommodate the optics assemblies, which will be bolted to the weldnecks.

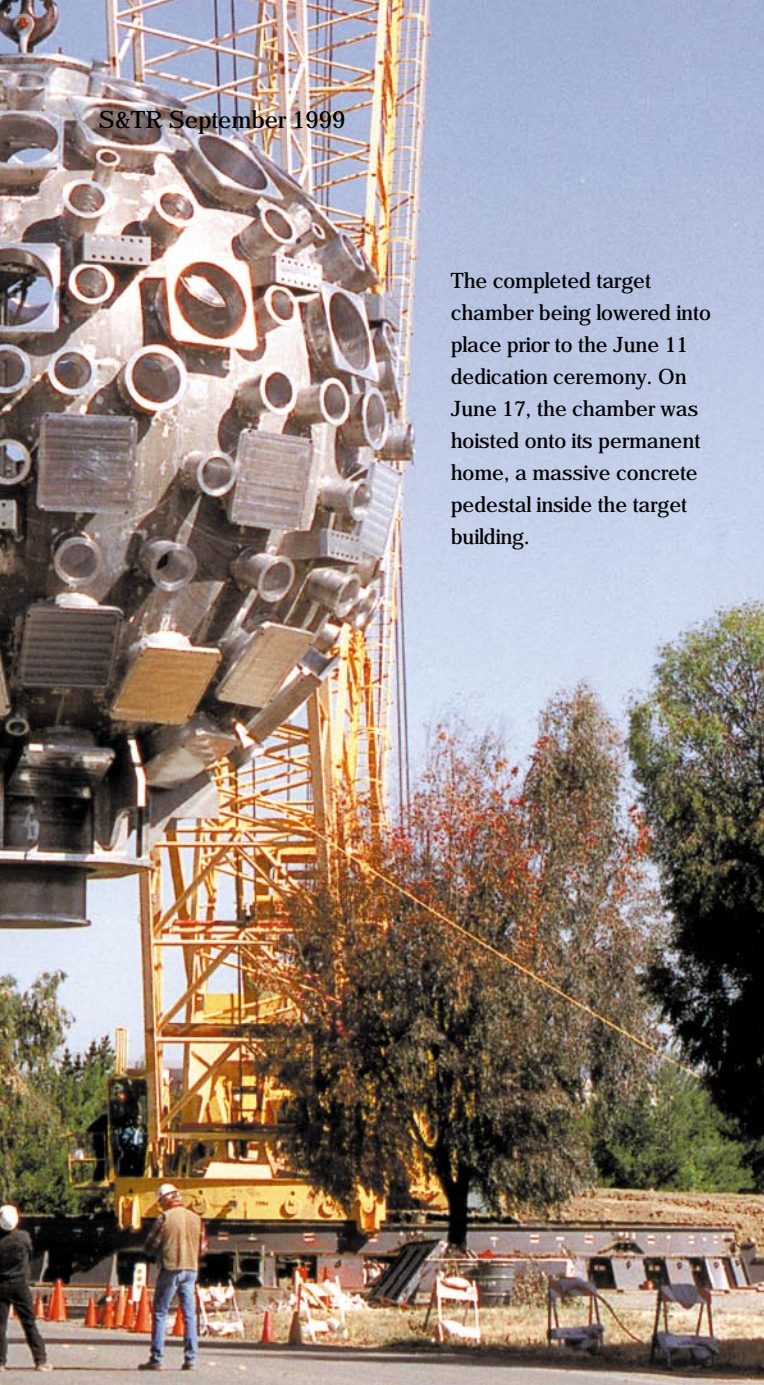


In addition, workers drilled 118 diagnostic-instrument ports with inner diameters varying from 15 to 70 centimeters.

### Achieving Extreme Sphericity

At regular steps along the way, the chamber was mapped with laser surveying instruments to ensure its sphericity. Wavrik notes that the American Society of Mechanical Engineers specification for spherical vessels is for the diameter to measure within 1 percent of specification, or within 10.16 centimeters for the 10-meter-diameter chamber. The Livermore-Sandia





The completed target chamber being lowered into place prior to the June 11 dedication ceremony. On June 17, the chamber was hoisted onto its permanent home, a massive concrete pedestal inside the target building.

The sphere was secured to the crane with a plate lowered vertically into the top port of the sphere and then turned horizontally to support the chamber from inside (similar to installing a togglebolt). "We all held our breath," recalled Livermore Director Bruce Tarter, when the chamber was lifted out of the enclosure and then placed on a Lampson Crawler (also borrowed from the test site) as an intermediate anchor for its public dedication.

A few days later, on June 11, the world got a good look at the chamber at the dedication ceremony. The extraordinary structure became an instant magnet for employees and visitors alike. As Britain's Graham Jordan, Deputy Under Secretary for Science and Technology, Ministry of Defense, remarked, the chamber looked as if it "simply landed one night" from outer space.

The following week, the chamber was hoisted onto a massive concrete pedestal installed inside the target building. Over the next two weeks, a combination of hydraulic jacks, roller assemblies and shims, and finally anchor bolts were used to adjust the chamber for final alignment and establish its proper elevation and sphere tilt.

This fall the exterior of the chamber will be tested for leaks and then encased in 40 centimeters of concrete with 0.1 percent boron to provide shielding from the neutron and gamma rays produced by the experiments. The concrete will be applied over steel rebar tied to the chamber with welded studs.

Following application of the concrete, the chamber's exterior will be sealed with epoxy paint, and the chamber

will be aligned and hung with the final optics assemblies, which will arrive next year. The chamber is expected to sag a bit from the 400 tons of the concrete shield and optics. As a result, the angle of the FOAs will be adjusted appropriately.

Although an unqualified success in its own right, the target chamber's completion serves as a striking symbol that NIF is only a few years away from history-making experiments as an essential component of DOE's Stockpile Stewardship Program.

—Arnie Heller

specifications called for final measurement within 0.5 percent, or 5.1 centimeters in 10 meters. In fact, the assembly crew achieved 0.25 percent, or 2.54 centimeters, across the entire diameter.

On June 5, the roof of the temporary enclosure was removed, and the target chamber was lifted out by an enormous crane, a 14-story-tall Manitowoc 4600 Ringer. Acquired from DOE's Nevada Test Site (and transported in pieces aboard 66 trucks), the crane weighs some 900 tons and has a lift capacity of 600 tons. It will remain on site for additional heavy-lifting construction jobs on NIF.

**Key Words:** final optics assemblies (FOAs), hohlraum, National Ignition Facility (NIF) target chamber, Nevada Test Site, Stockpile Stewardship Program.

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